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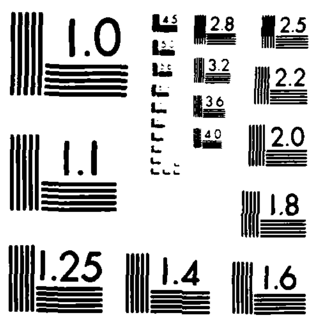

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water immersion; temperature regulation; metabolic rate; esophageal temperature; rectal temperature; skin temperature

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study examined both the thermal and metabolic responses of individuals in cool (30°C, n=9) and cold (18°C, n=7; 20°C, n=2) water. Male volunteers were immersed up to the neck for 1 h during both seated rest (R) and leg exercise (LE). In 30°C water, metabolic rate (M) remained unchanged over time during both R (115 W, 60 min) and LE (528 W, 60 min). Mean skin temperature ($\bar{T}_{sk}$) declined ($P<0.05$) over 1 h during R, while $\bar{T}_{sk}$ was unchanged during LE. Rectal (T_{re}) and esophageal (T_{es}) temperatures decreased ($P<0.05$) during R (ΔT_{re}, -0.5°C; ΔT_{es}, -0.3°C) and increased ($P<0.05$) during LE (ΔT_{re}, 0.4°C; $\bar{T}_{sk}$, 0.4°C).

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M, $\bar{T}_{sk}$, T_{re}, and T_{es} were higher ($P<0.05$) during LE compared with R. In cold water, M increased ($P<0.05$) over 1 h during R but remained unchanged during LE. T_{re} decreased ($P<0.05$) during R (ΔT_{re},-0.8°C) but was unchanged during LE. T_{es} declined ($P<0.05$)during R (ΔT_{es},-0.4°C) but increased ($P<0.05$) during LE (ΔT_{es}, 0.2°C). M, T_{re}, and T_{es} were higher ($P<0.05$) whereas $\bar{T}_{sk}$ was not different during LE compared with R at 60 min. In addition, T_{es} was higher ($P<0.05$) than T_{re} during R ($T_{es} - T_{re}$, 0.3°C) and LE ($T_{es} - T_{re}$, 0.3°C). These data indicate that LE is more effective than R in maintaining core temperatures in both cool and cold water. Also, immersion in cold water elicits differing core temperatures indicating that chest cavity temperature is maintained at a higher level than other core areas.

COMPARISON OF THERMAL RESPONSES BETWEEN

REST AND LEG EXERCISE IN WATER

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This study examined both the thermal and metabolic responses of individuals in cool (30°C, n=9) and cold (18°C, n=7; 20°C, n=2) water. Male volunteers were immersed up to the neck for 1 h during both seated rest (R) and leg exercise (LE). In 30°C water, metabolic rate (M) remained unchanged over time during both R (115 W, 60 min) and LE (528 W, 60 min). Mean skin temperature ($\bar{T}_{sk}$) declined ($P<0.05$) over 1 h during R, while $\bar{T}_{sk}$ was unchanged during LE. Rectal (T_{re}) and esophageal (T_{es}) temperatures decreased ($P<0.05$) during R (ΔT_{re},-0.5°C; ΔT_{es},-0.3°C) and increased ($P<0.05$) during LE (ΔT_{re}, 0.4°C; $\bar{T}_{sk}$, 0.4°C). M, $\bar{T}_{sk}$, T_{re}, and T_{es} were higher ($P<0.05$) during LE compared with R. In cold water, M increased ($P<0.05$) over 1 h during R but remained unchanged during LE. T_{re} decreased ($P<0.05$)during R (ΔT_{re},-0.8°C) but was unchanged during LE. T_{es} declined ($P<0.05$) during R (ΔT_{es},-0.4°C) but increased ($P<0.05$) during LE (ΔT_{es}, 0.2°C). M, T_{re}, and T_{es} were higher ($P<0.05$) whereas $\bar{T}_{sk}$ was not different during LE compared with R at 60 min. In addition, T_{es} was higher ($P<0.05$) than Tre during R (T_{es} - T_{re}, 0.3°C) and LE (T_{es} - T_{re}, 0.3°C). These data indicate that LE is more effective than R in maintaining core temperatures in both cool and cold water. Also, immersion in cold water elicits differing core temperatures indicating that chest cavity temperature is maintained at a higher level than other core areas.

Key words: water immersion; temperature regulation; metabolic rate; esophageal temperature; rectal temperature; skin temperature

Previous investigations have demonstrated that combined arm-leg exercise accelerates the drop in rectal temperature (T_{re}) compared with rest when individuals are immersed in cold water (10,12,15). Several factors have been proposed that explain the additional loss of body heat during this type of exercise despite the increased heat liberation through muscular contraction. First, movement of the limbs through water during exercise disrupts the surface film insulation on the skin thereby reducing the modest insulation provided by this water boundary layer (19). Second, exercise appears to increase the circulation to the extremities where peripheral heat loss is optimized due to the small diameter cylinders of the extremities and short conductive pathway for heat transfer from the limb core to the skin surface (26,28). Clearly, the exercising limbs considerably increase the overall heat conductance (27). Considering these factors and research findings, several investigators have concluded that rest is more effective than arm-leg exercise in maintaining a higher core temperature when individuals are immersed in cold water (3,10,12,15).

In contrast to these studies, recent research has systematically identified factors which argue in favor of exercise compared with rest for maintenance of T_{re} in water as low as 20°C. McArdle and colleagues observed that women respond poorly to cold-water stress when stationary, but when engaged in exercise they appear to have only modest depressions in core temperature (16,17). Other work demonstrated that the type of exercise performed in cold water altered the thermal responses of individuals (26). In this study (26), exercise which engaged the arms, either alone or in combination with the legs, lowered T_{re} to a greater extent compared with leg only exercise. In fact the difference between leg exercise and both arm and arm-leg exercise was similar in magnitude to that reported for rest compared with swimming or arm-leg exercise (9,15).

It is plausible that leg exercise may be equally or more effective than rest in maintaining core temperature while individuals are immersed in moderately cold water. Therefore, the present study was designed to compare the thermal and metabolic responses of individuals exposed to water to as low as 18°C during rest and leg exercise.

METHODS

Subjects. Nine healthy males with a mean (±SD) age of 23.6±5.2 years were medically cleared and volunteered to participate in the study. Table 1 illustrates the physical characteristics of the subjects. Each performed the experiments in the summer months and were unacclimated to the cold.

[Table 1 about here]

Procedures. Prior to experimental procedures body composition was assessed on all subjects by an underwater weighing procedure described by Goldman and Buskirk (8). Percent body fat was calculated from body density using the Siri equation (23). In addition, limb volumes were also obtained from both the legs and arms and were determined by water displacement (14).

For the experimental sessions, subjects dressed in nylon swim suits were harnessed with skin thermocouples and heat-flow disks and sat quietly for 15 min in a room maintained at approximately 22°C. An air-control measurement of all temperatures and heat flows was obtained prior to immersion.

Water experiments were performed in a 36,000 liter pool that was continuously circulated by air bubbled from the bottom. Subjects were immersed up to the neck in water at 30 and 18°C for 1 h during both rest and leg exercise. The two leanest subjects performed both tests in 20° water rather than in 18°C so as to minimize intersubject variability in core-temperature responses. Water-immersion exercise was performed on a specially designed leg ergometer (22) that has been further modified (26). One exercise power output was chosen for all subjects and both water temperatures (T_w). This intensity elicited an oxygen uptake ($\dot{V}O_2$) of about 1.6 l/min in water at 30°C. Subjects sat on the leg ergometer during the resting experiment. Values of $\dot{V}O_2$ were obtained at 5,15,30,45 and 60 min whereas rectal (T_{re}), esophageal (T_{es}), mean weighted skin ($\bar{T}_{sk}$) temperatures and mean weighted heat flow ($\bar{H}_c$) were continuously recorded throughout the immersion period.

Measurements. $\dot{V}O_2$ was determined by open-circuit spirometry. Expired air volumes were collected in a Tissot spirometer (Collins) and were corrected to standard conditions. Samples of expired air were analyzed for oxygen (Applied Electrochemistry S-3A) and carbon dioxide (Beckman LB-2) concentrations.

Metabolic rate (M) was determined from $\dot{V}O_2$ measurements. Measurements of $\bar{T}_{sk}$ were obtained by area weighting a five point thermocouple harness, where $\bar{T}_{sk} = 0.22\ T_{calf} + 0.28\ T_{thigh} + 0.28\ T_{chest} + 0.08\ T_{triceps} + 0.14\ T_{forearm}$. Thermocouples were covered with one layer of tape (Hy-tape Corp., New York, NY). T_{re} was recorded by the placement of a probe ~10 cm into the rectum while T_{es} was measured by the insertion of a thermistor into the naris and swallowed to the level of the heart. Heat-flow disks (RdF Corp., Hudson, NH) were applied with one layer of double-backed adhesive tape and placed adjacent to each skin thermocouple. Heat-flow disks were calibrated by the factory with a stated accuracy of 6-7% of actual heat flow. Weighting of individual heat flows was the same as described for the skin temperatures. T_w was measured at the five sites of the skin thermocouples at a distance of 10 cm from the body. Air temperature was measured in the vicinity of the subject's head.

All temperature and heat-flow data were recorded continuously by a Hewlett-Packard 9825 B computer both 15 min prior to and during the entire immersion period. Throughout each test both T_{re} and $\bar{T}_{sk}$ were continuously plotted so that the subjects could be monitored for safety. All water experiments were discontinued following the 1-h period or when T_{re} reached 35°C. Subjects were at liberty to withdraw from the study at anytime.

Statistical Analysis. All metabolic and thermal data were analyzed by the use of a two factor repeated measures design analysis of variance. Significant differences ($P<0.05$) on the ANOVA were further tested using the Tukey multiple range and interaction post-hoc test (4) to determine the differences between means. The 0.05 level of significance was chosen for all analyses.

RESULTS

Figure 1 illustrates M during R and LE as a function of time in both cool and cold water. In cool water, M was significantly higher ($P<0.01$) during LE as compared with R and M did not change across time during R and LE. In cold water, M was higher ($P < .05$) during LE compared with R across time. During the R exposure, M was significantly greater at min 30 and 60 compared with min 5 whereas there were no changes across time during LE. In cold water, M was significantly higher during LE compared with R across all time periods and T_w.

[Figure 1 about here]

Values of T_{es} are illustrated in Figure 2. During cool-water exposures, T_{es} increased ($P<0.05$) during the first 30 min of LE and remained unchanged for the final 30 min of exercise. In contrast, the R exposure showed no change during the first 30 min while T_{es} dropped ($P<0.05$) an average of 0.3°C during min 30 to 60. In cold water, T_{es} increased ($P<0.05$) with time during LE while there was a significant decline ($P<0.05$) during R. In cool and cold water, T_{es} was higher ($P<0.05$) during LE compared with R at both 30 and 60 min.

[Figures 2 and 3 about here]

The T_{re} responses were similar to those of T_{es} as shown in Figure 3. In cool water, T_{re} increased ($P<0.05$) across time during LE (0.4°C) whereas T_{re} steadily declined ($P<0.05$) with time during R (-0.5°C). In cold water, T_{re} remained unchanged across time during LE ($P>.05$) and R ($P=0.06$). In cool water, T_{re} was significantly higher during LE compared with R at 30 and 60 min; whereas in cold water the 0.5°C difference was not significant. In cold water, seven individuals (average % body fat = 17.8) performed both R and LE in 18°C whereas two subjects (average % BF = 13.3) were immersed in 20°C. As illustrated in Figure 4, the average values and variability of $\bar{T}_{sk}$ in cold water reflect the fact that all subjects were combined in the analysis. There was no significant difference between R and LE in either cool or cold water.

[Figures 4 and 5 about here]

Figure 5 illustrates a comparison between final T_{re} and T_{es} during R and LE in cool and cold water. In cool water, there were no differences ($P<0.05$) between T_{re} and T_{es} during R or LE conditions. However, after 60 min of cold water exposure the average T_{re} was significantly lower (0.3°C) than T_{es} during both R and LE.

DISCUSSION

Water-immersion exercise has been shown to either increase (3,10,12,15) or decrease (6,17) the rate of rectal temperature (T_{re}) decline when compared with rest. Rest appears to be more advantageous than arm-leg exercise for maintenance of T_{re} when water temperatures (T_w) are low (3,10,12,15), whereas the reverse is true in warmer water (6,7). The crucial T_w at which the advantage shifts between rest and exercise is approximately 20°C though several physical and physiological factors appear to modify this particular temperature. Large subcutaneous fat and total body fat is an advantage to the exercising person compared with resting (15,16,17) and most likely acts to lower this crucial T_w.

In addition to insulation, core temperature responses of individuals immersed in various T_w have been shown to be dependent upon the particular exercise intensity (6,19,26). It appears that the higher T_{re} response from high intensity exercise may be explained in part by the return of heat that is liberated in the exercising muscles to the core for core temperature maintenance rather than loss of this heat to the environment (26). Therefore, exercise intensity also acts to lower the T_w at which rest would be more advantageous than exercise during immersion.

Recent work from our laboratory has shown that the type of exercise may also act to modify this crucial T_w (26). In this study, leg only exercise elicited a higher T_{re} compared with either arm or combined arm-leg exercise performed at the same metabolic rate for 1 h. In fact, the differences in T_{re} values between leg and both modes of arm exercise were of similar magnitude as reported by both Keatinge (15) and Hayward, et al. (9) for the differences between rest and exercise. Therefore, it is quite possible that leg only exercise should minimize differences in T_{re} when compared with rest.

The present study examined the relationship between rest and exercise involving the legs only in cool and moderately cold water. These data demonstrate that 1 h of leg exercise resulted in a higher core temperature response compared with rest. In addition, leg exercise was effective in maintaining a near normal core temperature throughout 1 h of immersion in water at about 18°C and these findings are supported by others (18).

It is clear that exercise in general reduces the total body insulation. A substantial amount of heat is liberated to the water environment because of the increased blood flow to the limbs where the large surface area to mass ratio and small diameter cylinders of the limbs establish an ideal condition for heat transfer to the water. Exercise which engages the legs only appears to favor heat retention in moderately cold water compared with arm-leg exercise (26). During LE in cool water, the insulation in the non-exercising arms increases because of a reduced circulatory convective heat transfer (27) as well as a reduced forced convection at the skin's surface (26). The legs act as a thermal window that allows for heat loss during exercise in cold water. Although heat transfer to the water is elevated during LE, these present data indicate that a portion of the metabolic heat is retained in the core. In fact, compared with R, LE retains more heat in the core as illustrated by the higher T_{es} and T_{re} values.

In addition to higher core temperatures during LE compared with R, T_{es} were significantly higher than T_{re} during the cold-water exposures (Fig. 5). This is in contrast to exercise performed in cool water in the present study and in fact the exercise literature in temperate air environments. Studies performed in temperate air show that the T_{es} and T_{re} values are equivalent after 30-60 min of exercise despite the performance of leg only exercise (1,20,21). In the present investigation, T_{re} and T_{es} responses were not different following 60 min of rest or exercise in water at 30°C. However, T_{es} was 0.3° higher than T_{re} after 1 h both at rest and during leg exercise in cold water.

Several studies have documented differences between rectal and other core temperatures (5,7,11,13,15). Also, Keatinge (15) reported lower T_{es} compared with T_{re} during exercise in 15°C water, which might be the results of combined arm and leg exercise in that study. Cranston, et al. (7) suggests that T_{re} may be a function of the local blood flow in the rectum and adjacent tissues where the probe is positioned. In cold water the pronounced sympathetic tone could reduce blood flow in the pelvic vascular bed and partition this area from circulating heat input from arterial blood. In light of the work of Aulick, et al. (2) who described T_{re} as the dynamic interplay during exercise between a) arterial temperature, b) the rate of blood flow perfusing the pelvic area, c) the temperature gradient between the blood and and tissue, and d) the local metabolism, it is plausible that local cooling of the tissues in the pelvic floor in combination with reduced blood flow to the visceral tissues surrounding the rectal probe, present a thermal gradient which might explain the lower T_{re} compared with T_{es}.

These findings have important theoretical and practical implications. First, moderate-intensity exercise with the legs only is an effective means of maintaining core temperatures when individuals are immersed in cold water (18-20°C). In fact this type of exercise is more effective than rest in preventing the drop in deep body temperature over time. These results may have particular application for situations involving cold water accidental immersion. However, rest rather than exercise is generally advocated when individuals become immersed in ocean water (10). Leg exercise may also be as effective as rest when individuals become accidentally immersed in warmer ocean water. Further research needs to be directed toward colder water exposures to determine if leg exercise should be considered for body heat retention.

Second, these data should also be considered with regards to theoretical and biophysical models and equations which assume a uniform or well mixed core temperature and attempt to predict body temperature responses in water (9,24,25). Hayward, et al. (9) used the time course of T_{re} between 15 and 25 min of exposure to predict the time an individual would reach a core temperature of 30°C. The present data would calculate substantially different times to this temperature depending upon whether T_{es} or T_{re} values were used. It may be argued that T_{es} may be a better indication of heart temperature in an individual immersed in cold water, and therefore a more appropriate core temperature measurement to use for mathematical predication. Theoretical models of heat transfer should also consider these present findings. Strong and Goldman (24) in developing their heat transfer model for example, assume that the body core is the source of metabolic heat and that the heat transfer is from a uniform core to the subcutaneous tissue. The ultimate impact of the non-uniform core temperature upon these types of models will more clearly be determined when additional work identifies a) the magnitude of the differences in temperature between core areas, b) the relationship between environmental-exercise conditions and the temperature differences within the core, and c) the identification of the core-temperature measurement that best relates to survival.

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The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Human subjects participated in these studies after giving free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on the Use of Volunteers in Research. Approved for public release; distribution unlimited.

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TABLE 1. Physical Characteristics of the Subjects.

Subject	Ht	Wt	LBW	%BF	Skin	A_D	A_D/Wt	LV_A	LV_L
$\bar{X}$	176.7	76.7	63.8	16.8	124.6	1.97	2.54	2.59	10.48
SD	8.6	10.4	8.8	3.0	35.0	0.14	0.17	0.33	1.81

Ht, Height (cm); Wt, Weight (kg); LBW, Lean Body Weight (kg); %BF, Percent Body Fat; SKIN, Sum of 10 Skinfolds (mm); A_D, Surface Area by Dubois Formula (m^2); A_D/Wt ($cm^2 \cdot kg^{-1} \cdot 10^{-2}$); LV_A, Limb Volume of Arms (ℓ); LV_L, Limb Volume of Legs (ℓ)

FIGURE LEGEND

Figure 1. Metabolic rate during 1-h exposure to cool (left) and cold water (right) during rest and leg exercise ($\bar{X}$±SD).

Figure 2. Esophageal temperature responses during 1-h exposure to cool (left) and cold (right) water during rest and leg exercise ($\bar{X}$±SD).

Figure 3. Rectal temperature responses during 1-h exposure to cool (left) and cold water (right) during rest and leg exercise ($\bar{X}$±SD).

Figure 4. Mean weighted skin temperatures during 1-h exposure to cool (left) and cold (right) water during rest and exercise ($\bar{X}$±SD). Cold water values combines 18°C (n=7) and 20°C (n=2) exposures.

Figure 5. Comparison of esophageal (T_{es}) and rectal (T_{re}) temperatures during rest (R) and leg exercise (LE) in cool (left) and cold (right) water.

Figure 1

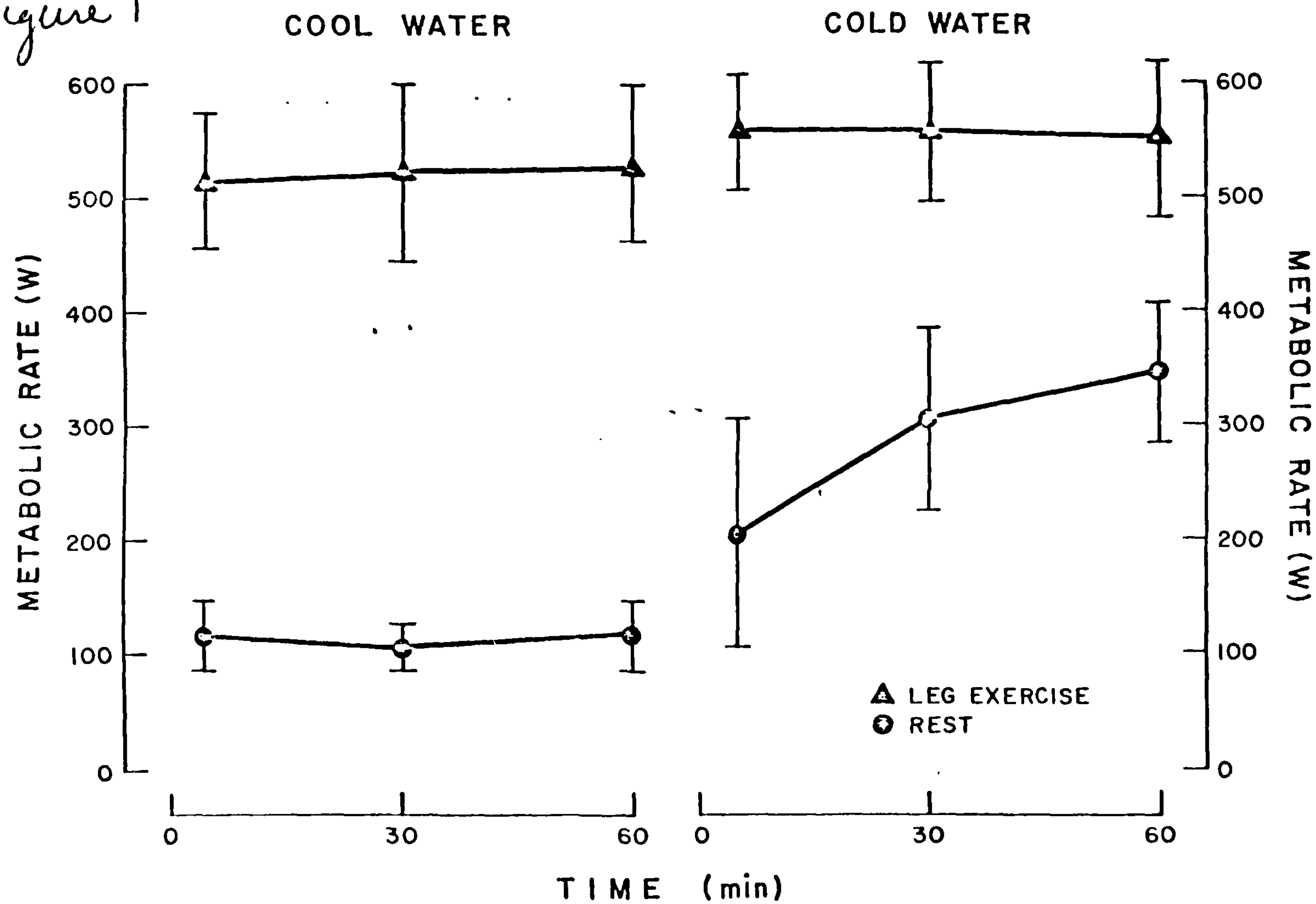
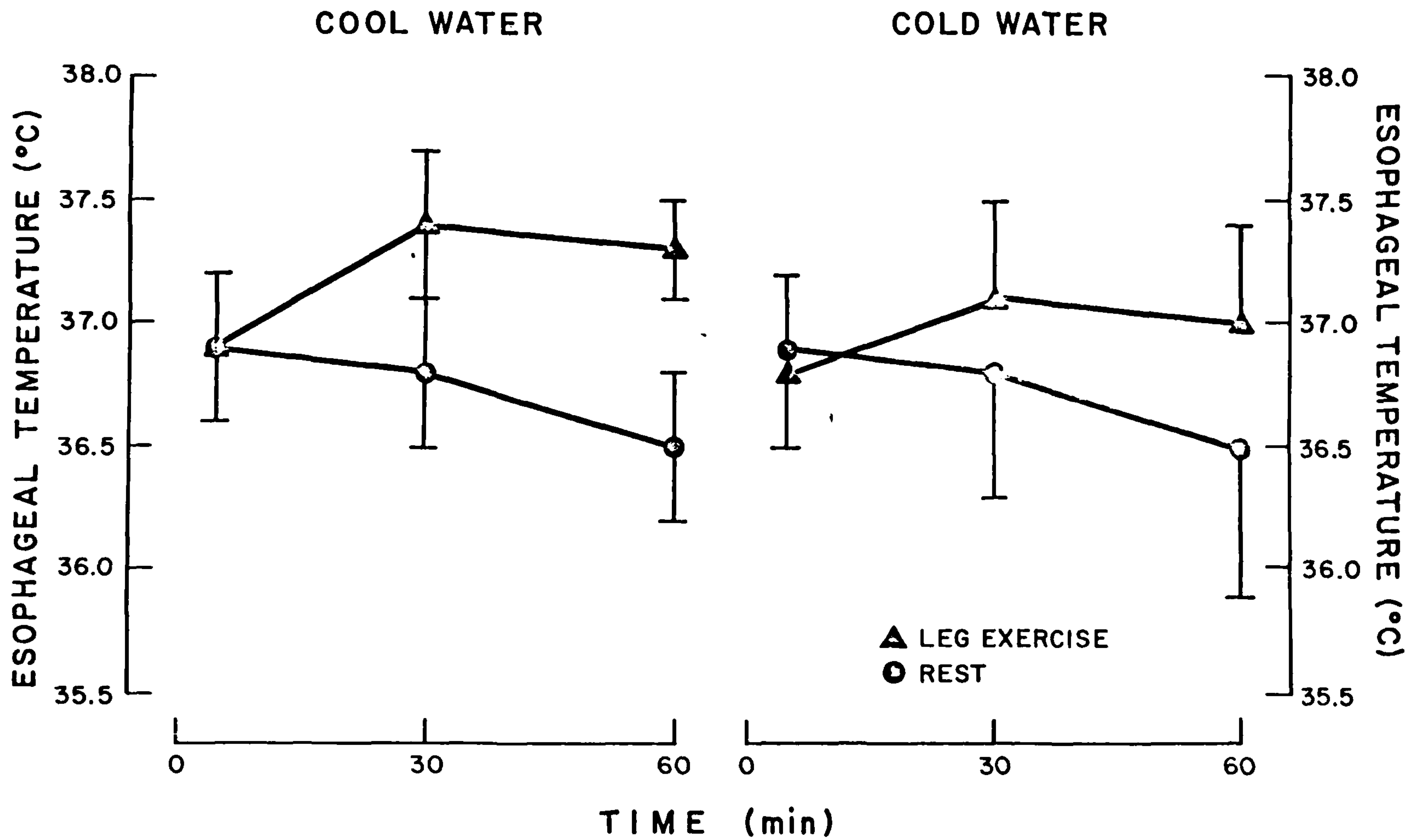

COOL WATER
COLD WATER
METABOLIC RATE (W)
600
500
400
300
200
100
0
LEG EXERCISE
REST
0
30
60
TIME (min)

Figure 2



COOL WATER
COLD WATER
ESOPHAGEAL TEMPERATURE (°C)
38.0
37.5
37.0
36.5
36.0
35.5
ESOPHAGEAL TEMPERATURE (°C)
LEG EXERCISE
REST
0
30
60
0
30
60
TIME (min)

Figure 3

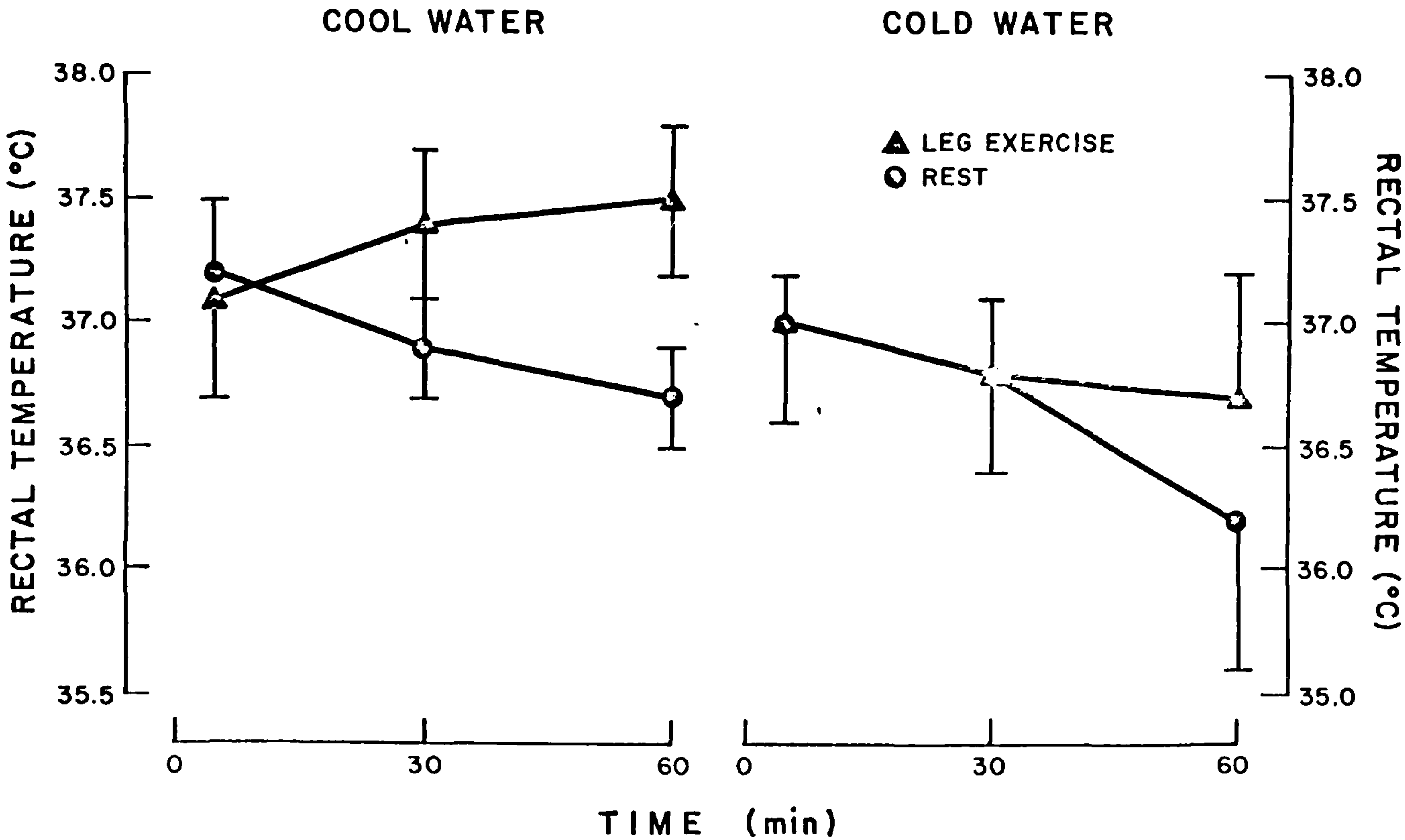
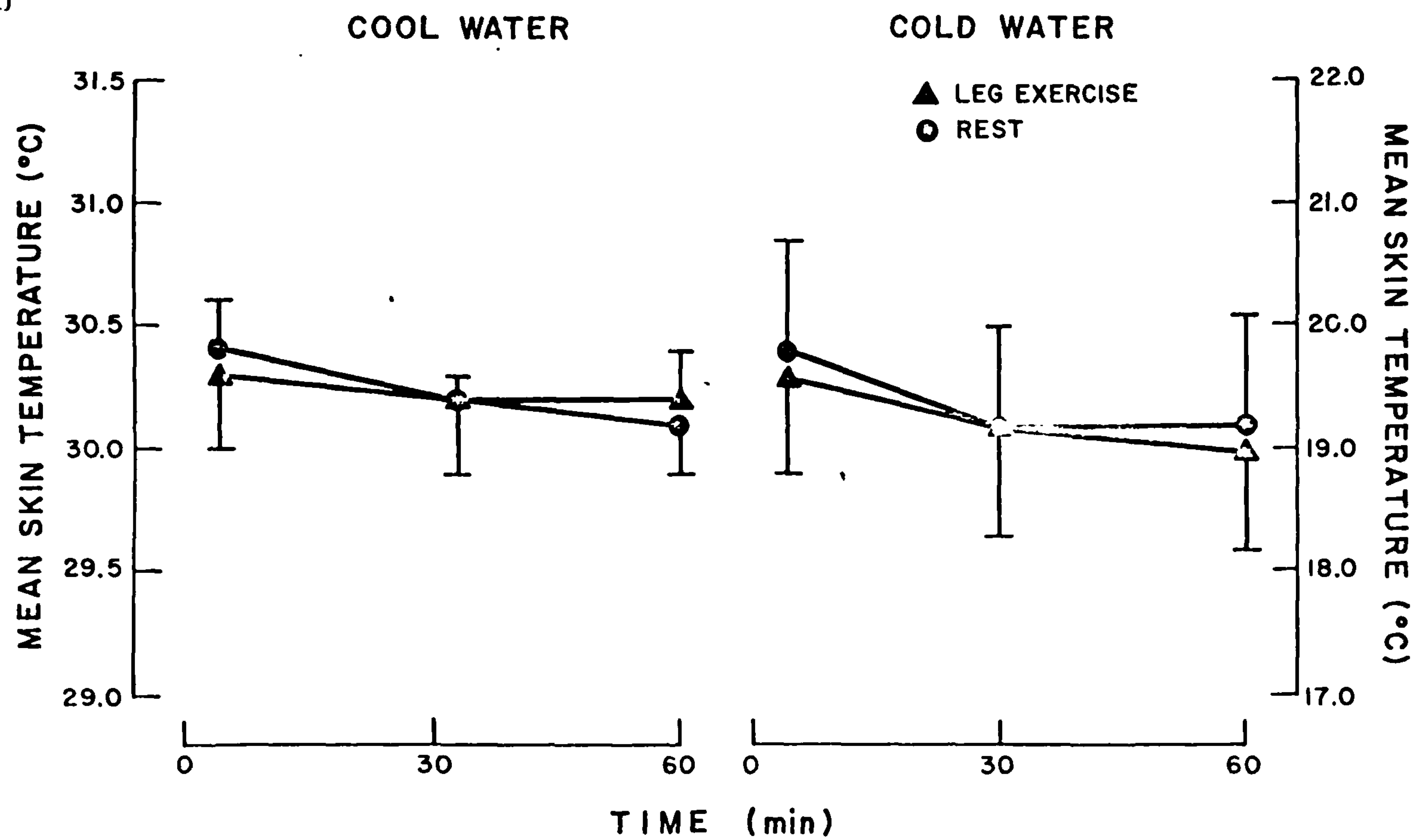
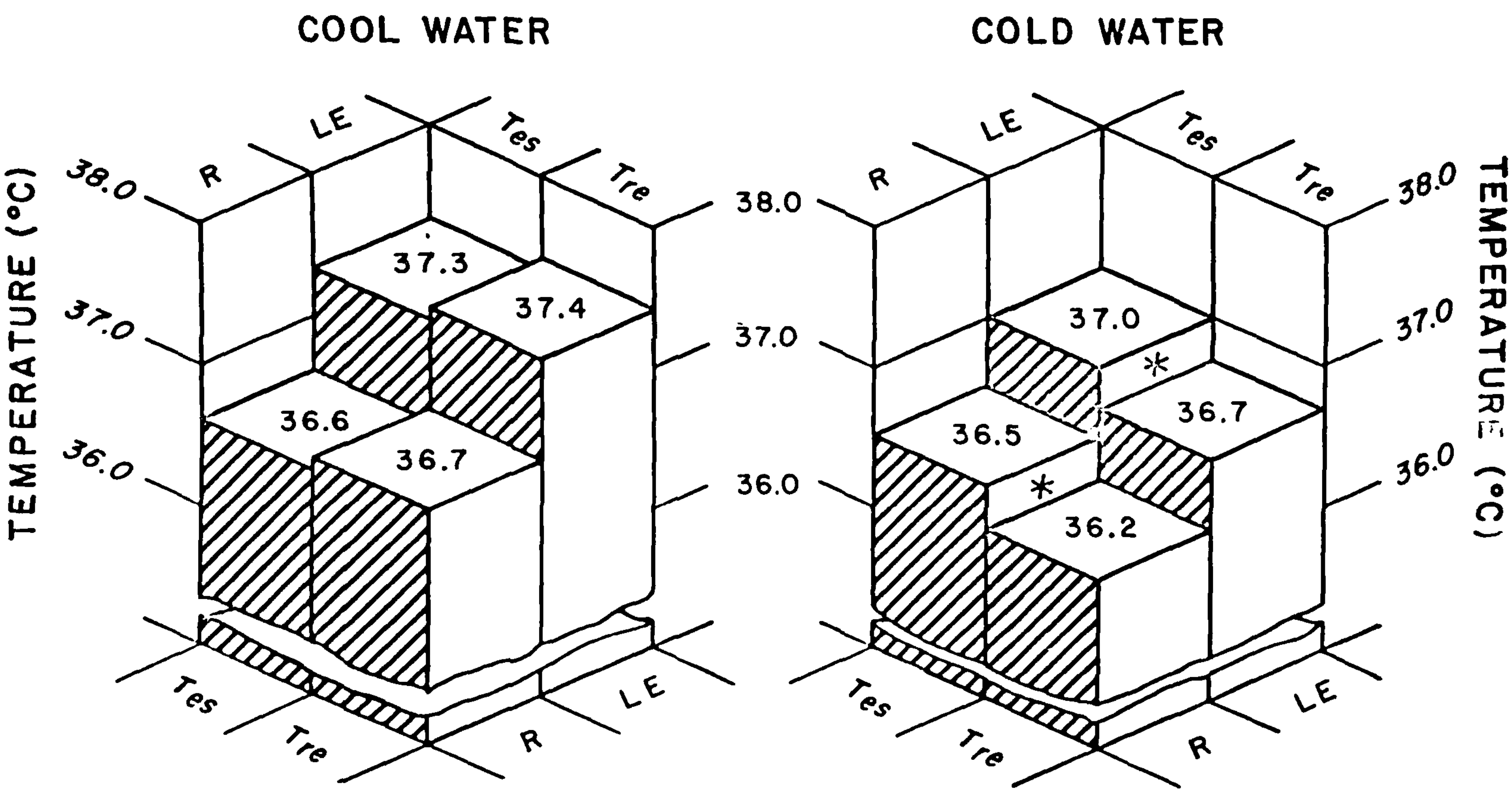

COOL WATER
COLD WATER
LEG EXERCISE
REST
RECTAL TEMPERATURE (°C)
38.0
37.5
37.0
36.5
36.0
35.5
35.0
0
30
60
TIME (min)

Figure 4



COOL WATER
COLD WATER
LEG EXERCISE
REST
MEAN SKIN TEMPERATURE (°C)
31.5
31.0
30.5
30.0
29.5
29.0
22.0
21.0
20.0
19.0
18.0
17.0
0
30
60
TIME (min)

FIGURE 5



COOL WATER
COLD WATER
TEMPERATURE (°C)
38.0
37.0
36.0
R
LE
Tes
Tre
37.3
37.4
36.6
36.7
37.0
36.7
36.5
36.2
*
TEMPERATURE (°C)